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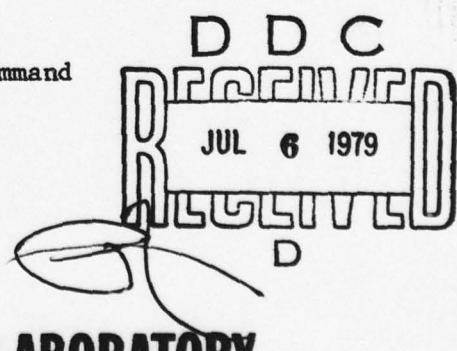
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**author:** Thorndyke Roe, Jr., Sylvio Tuccillo,  
and Richard Lorenzana

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An additive was sought for seawater such that the mixture could be sprayed on beach sand to make a trafficable crust for amphibious warfare operations. None met all requirements, but a proprietary polyisocyanate met most. It could not be premixed with seawater, but it penetrated seawater-wet sand and produced a 6-inch-thick crust of 100 psi compressive strength in one hour at a cost of \$8 to \$10 for materials per square foot of sand stabilized.

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## EXECUTIVE SUMMARY

At present, the Marine Corps has a capability to provide expedient traffickable soil surfacings for beach crossings and storage areas. However, the systems used, such as the laying of matting materials or the Advanced Multipurpose Surfacing System, present a logistics problem because everything needed must be shipped to the site. This problem could be reduced considerably through greater use of native materials such as sand for aggregate and seawater as a diluent for a binder concentrate.

The Civil Engineering Laboratory investigated seawater-soluble binders which could be added to beach sand without mixing or compacting. An unconfined compressive strength of 100 lbs/sq in. was required after a short curing period. Twenty-one products were investigated. None met all of the requirements, which were:

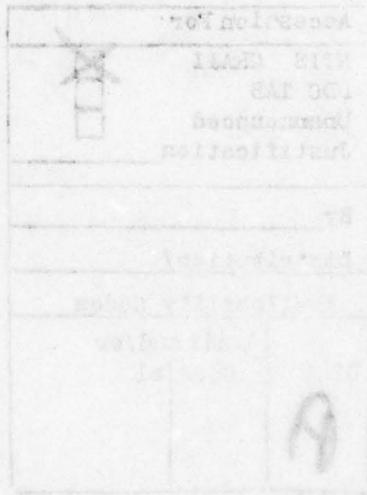
- (1) Complete solubility in seawater
- (2) Viscosity near that of seawater
- (3) Two-hour cure with 100 psi unconfined compressive strength
- (4) Insoluble in water when cured

A proprietary isocyanate product, Takenaka T-018, met most of the requirements. It could not be premixed with seawater, but it penetrated seawater-wet sand and produced a 6-in. crust of 100 psi unconfined compressive strength in 1 hour. Cost (1976) of the material was \$8 to \$10 per square foot of sand stabilized. This product is Japanese made, but is to be licensed for manufacture in the United States.

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## INTRODUCTION

There is a continuing need to improve the capability of MARCORPS and Naval Construction Force engineer units to provide expedient trafficable soil surfacings in combat zones. Of particular interest are beach crossings and materiel storage areas associated with amphibious landings. Capabilities already exist. One is in the form of prefabricated mattings (i.e., MOMAT, a fiberglass-reinforced matting delivered in rolls, and AM-2 aluminum landing mat); the other is a fiberglass-reinforced resin that is sprayed in place as a liquid and hardens to traffickable condition in 30 minutes (i.e., Advanced Multipurpose Surfacing System). However, all of these systems entail shipping 100% of the materials to the amphibious objective area, thereby constituting a logistic burden. It would be beneficial if that burden could be reduced through greater utilization of native materials on-site at the amphibious target area. The two most abundant materials at such sites are seawater and, in most cases, beach sand. Therefore, it would be desirable if a hard, traffickable crust could be made on the beach sand using seawater and an additive to cement the sand particles together to form such a crust. Preferably, the seawater mixture would be sprayed onto the sand surface where it would percolate down and provide the cementing action without being mechanically mixed with the sand.

The Civil Engineering Laboratory was tasked to investigate methods and materials for the stabilization of loose beach sand by adding chemical binders to seawater and spreading the resultant solution on the sand surface without mixing and, preferably, without compaction. High permeability beach sands should be stabilized at depths from 15 cm (6 inches) to 30 cm (1 foot) and should have an unconfined compressive strength of at least 100 lbs/sq in. after a short curing period. This would provide a roadway surface for military vehicles during the early stages of an operation.

Specifically, the requirements of the binder are:

- (1) A liquid or solid material which can be dissolved in seawater to form a dilute solution.
- (2) The dilute solution shall have a viscosity near that of seawater and be able to penetrate rapidly into beach sand.
- (3) The binder-sand shall setup in 1 to 2 hours and provide 100 lbs/sq in. unconfined compressive strength.
- (4) The binder-sand, after set up, shall not be affected by water.

A thorough review of the literature failed to yield any method of sand or soil stabilization suitable for the desired end use. Undesirable binder characteristics included:

- (1) Relatively slow setup by evaporation of water
- (2) Slow curing by chemical reaction
- (3) Excessive viscosity, precluding percolation through sand and necessitating mechanical mixing
- (4) Incompatibility with seawater
- (5) Poor mechanical strength

A letter of inquiry about possible candidate materials was sent to 155 corporations. The following specification was included with that letter:

The stabilizers may be in liquid or solid form, single or dual component, easily miscible with seawater to provide a low viscosity solution. The solution should be applicable by distributor and capable of percolation into sand to depths of 6 inches to 1 foot.

For candidate materials, the following information was requested:

1. Name, descriptive procedures, and test reports
2. Major components
3. Recommended dilution
4. Recommended application rate - per square yard, per cubic foot
5. Cost per gallon, FOB

The letter also stated that the following tests for candidate materials should be conducted at the Civil Engineering Laboratory:

1. Depth of percolation into sand
2. Gelling or curing rate
3. Unconfined compression test
4. Resistance to water
5. Resistance to erosion

Twenty companies offered one or more candidate materials. Some of these companies furnished samples; others did not, so the required materials were purchased. Nonproprietary candidate binder materials were also purchased.

Despite the requirements stated in the letter of inquiry, many of the products recommended did not meet those for miscibility with seawater, low solution viscosity, and cure time. However, because of the small number of products which did appear to meet the requirements, all those

recommended were evaluated. Also, test specimens which used conventional binders, such as portland cement or gypsum cement, were made for comparison.

The products used in this study are listed in Table 1.

## EXPERIMENTAL

Dry beach sand, approximately 600 grams, was weighed and, in most cases, seawater was added to attain a desired moisture content. A piece of filter paper was fitted around one end of a clear plastic cylinder and held in place with a rubber band. This cylinder, 6 cm (2-5/16 inches) in diameter and 20.4 cm (8 inches) high, was placed in a Petri dish. The moist sand was added to the cylinder to a depth of 15.2 cm (6 inches), after which the candidate binder was poured onto the surface. The time to a "dry top" surface was determined, and, when possible, the time to maximum penetration. After a prescribed cure time, the filter paper was removed from the cylinder and both top and bottom surfaces of the sand/binder core were examined and probed for hardness. Cores which had not hardened were removed from the cylinder and discarded. Cores which had hardened top surfaces, but in which the binder had not penetrated to the full depth of the sand column were removed, and the loose sand was discarded. If the minimum penetration of the binder was at least half the depth of the sand column, the sample ends were cut off square and the sample was tested for compressive strength. Samples where the binder penetration was less than half the column depth were discarded, but if the binder appeared to have promise, the experiment was repeated with a larger volume of binder. Cores which had hardened from top to bottom were removed from the mold and set aside for compressive strength tests.

Viscous candidate binder materials were mixed with sand which contained the desired amount of seawater. Then the binder-sand mixture was transferred to a 6x20.4 cm plastic cylinder fitted with a piece of filter paper on one end. After the prescribed curing time, the core end surfaces were examined and, if sufficiently hard, the core was removed from the cylindrical mold and set aside for compressive strength determination.

The experiments conducted on products which were investigated are described in the Appendix.

## FINDINGS

None of the materials evaluated met all of the criteria listed in the introduction of this report, but the polyisocyanate materials, although they could not be premixed with seawater, were compatible with wet sand and met the requirements for penetration, cure time, strength, and water resistance after cure. Specifically, Takenaka T-018 (90g), plus C-001 accelerator (1.8 - 2.7g) gave results superior to all of the other materials evaluated. At a coverage rate of 91.8 - 92.7g (83.5 - 84 ml) for a surface area of 28.3 sq cm, 2741 - 2757 ml(0.72 - 0.73 gal)

per 929 sq cm (1 sq ft) would be required to stabilize sand to a depth of 15.2 cm (6 inches). At present prices, the cost would be \$8.00 to \$10.00 per square foot for materials.

## CONCLUSION

It is concluded that a polyisocyanate material can be used to stabilize wet beach sand to a depth of 15.2 cm (6 inches) without premixing and will cure in 1 hour to yield a solid mass with an unconfined compressive strength greater than 100 psi.

## RECOMMENDATIONS

It is recommended that:

1. Field scale trials be conducted with polyisocyanate binders for beach sand.
2. As new binder materials are made available, they should be evaluated.

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Table 1. Binder Materials Used in This Study

Product	Description	Manufacturer/Supplier
Cal Seal <sup>a</sup>	Gypsum cement	Halliburton Co.
CMS-2S	Asphalt cement emulsion	Chevron USA
Curasol AK	Polymer emulsion	American Hoechst Corp.
Derkane 470-45	Polyester resin (vinyl ester)	The Dow Chemical Co.
Edoco X-21111-1	Epoxy resin, polyamide cured	Edoco Technical Products
Epon 815	Epoxy resin	Shell Chemical Co.
Ethyl Silicate-40	Silicate ester	Union Carbide Corp.
Gypsum <sup>b</sup>		
Orzan AL-50	Ammonium lignin sulfonate	Crown Zellerbach
PDO-K	Proprietary asphalt product	Chevron USA
Portland Cement, Type II, Low Alkali		Southwestern Portland Cement Co.
Regulated Set Cement	Early strength cement	Huron Cement Co.
Resorcinol Waterproof Glue	Resorcinol adhesive	U.S. Plywood
Sodium Silicate		
Soiltex	Lignin sulfonate	Protex Industries, Inc.
T-009	Polyisocyanate	Takenaka Komuten Co., Ltd.
T-018	"	"
T-025	"	"
T-118	"	"
Terra Krete	Synthetic resin emulsion	Kingman Chemical Co.
X-2000	Vegetable oil base polymer	Chem-Crete Corp.

<sup>a</sup>Mixed with Type II cement.<sup>b</sup>Mixed with Portland Cement or Regulated Set Cement in some formulations.

## APPENDIX

### EXPERIMENTS CONDUCTED

CAL SEAL:

This gypsum cement (22.9g) was mixed with Type II cement (38.1g) and water (121g) and poured onto a 10.8 cm column of dry sand (508g). When an attempt was made to remove the sample from the mold after 16 hours, the sample ruptured.

In a second experiment, Cal Seal (73.8g) was mixed with Type II cement (73.8g) and water (62g) and poured onto a column of dry sand (738g). After a 72-hour cure, the unconfined compressive strength was 195 psi.

In a third experiment, Cal Seal (113.8g) was mixed with Type II cement (75.8g) and water (147g) and poured onto a column of dry sand (632g). After a 72-hour cure, the unconfined compressive strength was 513 psi.

In a fourth experiment, Cal Seal (62.4g) was mixed with Type II cement (47.6g) and water (115g) and poured onto a column of dry sand (520g). After curing, the unconfined compressive strength was 110 psi.

CMS-2S:

This asphalt cement emulsion (90g) was poured onto a column of sand (600g) wet with seawater (12g). It penetrated about  $\frac{1}{2}$  inch in three hours.

In a second experiment, CMS-2S (45g) was mixed with seawater (45g) and poured onto a column of sand (600g) wet with seawater (12g). A "dry top" was obtained in 20 minutes. After an extended cure time, the material did not harden.

In a third experiment, CMS-2S (58.5g) was mixed with seawater (31.5g) and poured onto a column of sand (600g) wet with seawater (12g). A "dry top" was obtained in 18 minutes, but after an extended cure time, the material did not harden.

CURASOL® AK:

This polymer emulsion (75ml) was mixed with one percent (0.8g) wetting agent, Igepal® CO-630, and poured onto a 6 cm diameter X 12.7 cm column of sand (300 ml) which contained four percent moisture. There was poor penetration, so the sand and binder were removed from the mold, mixed, and returned to the mold. The column height decreased to 8.25 cm. After 16 hours, there was no cure.

In a second experiment, Curasol® AK (52.5ml) was mixed with seawater (22.5ml) and Igepal® CO-630 (0.8g). Malachite green oxalate was added as a dye tracer. When poured onto a column of sand (300ml) which contained 4% moisture, it percolated very slowly. After 16 hours, there was no cure.

In a third experiment, Curasol<sup>®</sup> AK (22.5ml) was mixed with seawater (52.5ml) and Igepal<sup>®</sup> CO-630 (0.8g). Malachite green oxalate was added as a dye tracer. When poured onto a column of sand (300ml) which contained 4% moisture, good penetration occurred. The column height decreased from 12.7 cm to 11.4 cm. After 16 hours, there was no cure. The solution had penetrated the entire column.

DERAKANE<sup>®</sup> 470-45:

This vinyl ester polyester resin (45% styrene) was mixed with N-phenylmorpholine promoter (3.45g) and Cadox<sup>®</sup> BCP catalyst (0.35g) and poured onto a column of sand (600g) with four percent added seawater. After 24 hours, the top surface was soft and the bottom surface had not cured. When removed from the mold five days later, the bottom half crumbled and the top half was sticky.

In a second experiment, the quantities of promoter and catalyst were doubled. Ninety grams of the promoted and catalyzed resin were mixed with dry sand (600g) and placed in a cylindrical mold. After a 24-hour cure, the mold was stripped off. The top two inches of sand crumbled. The lower four inches was squared off and tested. The unconfined compressive strength was 1012 psi.

EDOCO<sup>®</sup> X-21111-1:

This polyamid-cured epoxy resin (56g of a 1:1 mixture) was mixed with sand (561g) wet with four percent added seawater and placed in a cylindrical mold. Mixing was very difficult because of the high viscosity of the catalyzed resin. The unconfined compressive strength, after a 24-hour cure, was 58 psi.

EPON<sup>®</sup> 815:

This Versamid<sup>®</sup>-cured epoxy resin (84g of a 1:1 mixture) was mixed with dry sand (557g) and placed in a cylindrical mold. Mixing was very difficult because of the high viscosity of the catalyzed resin. The unconfined compressive strength, after a 24-hour cure, was 1710 psi.

ETHYL SILICATE 40:

This silicate ester (50g) was hydrolyzed with one percent hydrochloric acid (10g) and then mixed with water (100g). It was poured onto a column of dry sand (585g). It percolated and a "dry top" was noted after 16 minutes. After 48 hours, a very friable product was obtained.

GYPSUM:

This natural hydrated calcium sulfate was mixed with sand (600g) with 17.5 percent added seawater and transferred to a cylindrical mold. After a 4-hour cure, the unconfined compressive strength was 75 psi.

The above experiment was repeated, except that the cure time was increased to 24 hours. The unconfined compressive strength of this sample was 116 psi.

In a third experiment, gypsum (120g) was mixed with sand (600g) with 20 percent added seawater. After a 4-hour cure, the unconfined compressive strength was 171 psi.

The above experiment was repeated, except that the cure time was increased to 24 hours. The unconfined compressive strength of this sample was 228 psi.

In a fifth experiment, gypsum (150g) was mixed with sand (600g) with 20 percent added seawater. After a 4-hour cure, the unconfined compressive strength was 448 psi.

The above experiment was repeated, except that the cure time was increased to 96 hours. The unconfined compressive strength was 561 psi.

ORZAN<sup>®</sup> AL-50:

This solution of ammonium lignin sulfonate (30g) was mixed with seawater (60g) and poured onto a column of sand (600g) wet with seawater (24g). The solution percolated rapidly (21 seconds to "dry top"), but did not cure.

In a second experiment, Orzan<sup>®</sup> AL-50 (45g) was mixed with seawater (22.5g) and sodium dichromate (22.5g) and poured onto a column of sand (600g) wet with seawater (24g). Although this solution percolated to a "dry top" in 3 minutes, 15 seconds, the total depth of penetration was 6.4 cm. The sample was not tested.

In a third experiment, Orzan<sup>®</sup> AL-50 (45g) was mixed with seawater (22.5g) and sodium dichromate (22.5g). This solution was mixed with sand (600g) wet with seawater (12g) and placed in a plastic cylinder. After an 82-hour cure, the unconfined compressive strength was 42 psi.

In a fourth experiment, Orzan<sup>®</sup> AL-50 (45g) was mixed with seawater (45g) and sodium dichromate (10g) and poured onto a column of sand (600g) wet with seawater (24g). The solution percolated to a "dry top" in one minute. After a 90-hour cure, the unconfined compressive strength was 26.5 psi.

PDO-K<sup>®</sup>:

This proprietary asphalt emulsion product (90g) was poured onto a column of sand (600g) wet with seawater (12g). There was essentially no penetration nor hardening.

In a second experiment, PDO-K® (45g) was mixed with seawater (45g) and poured onto a column of sand (600g) wet with seawater (12g). A "dry top" was obtained in three minutes and the solution penetrated 12.7 cm in five minutes. No hardening occurred.

In a third experiment, PDO-K® (60g) was mixed with seawater (30g) and poured onto a column of sand (600g) wet with seawater (24g). A "dry top" was obtained in 5 minutes, 43 seconds. After a 24-hour period, no hardening had occurred.

In a fourth experiment, PDO-K® (45g) was mixed with seawater and poured onto a column of sand (600g) wet with seawater (24g). A "dry top" was obtained in 75 seconds, but no hardening had occurred after 24 hours.

In a fifth experiment, PDO-K® (90g) was poured onto a column of sand (600g) wet with seawater (24g). The maximum penetration of this solution was approximately  $\frac{1}{2}$  inch.

#### PORLAND CEMENT:

This cement (150g) was mixed with dry sand (600g) and seawater (150g) and transferred to a cylinder which was then tapped on a table to consolidate the mix. The mix was very soupy, but after a 24-hour cure, its unconfined compressive strength was 199 psi.

#### PORLAND CEMENT - GYPSUM:

Portland cement (45g) and gypsum (45g) were mixed with dry sand (600g), then seawater (90g) was added and mixed. Two batches of this mix were made and each was transferred to a cylinder. Compaction was accomplished by tapping the cylinders vertically on the table. One mix was cured for 19 hours; its unconfined compressive strength was 35 psi. The second mix was cured for 24 hours; its unconfined compressive strength was 53 psi.

In a second experiment, two mixes were prepared. In each, Portland cement (45g) and gypsum (45g) were mixed with sand (600g) and each dry mix was placed in a cylinder. Then each cylinder and its contents were tapped vertically on a table. Seawater (90g) was added to each cylinder and allowed to percolate. One mix cured for 18 hours; its unconfined compressive strength was 67 psi. The second mix was cured for 24 hours; its unconfined compressive strength was 81 psi.

In a third experiment, Portland cement (45g) and gypsum (45g) were mixed with dry sand (600g), then seawater (120g) was added and mixed. The mix was transferred to a cylinder and the sides of the cylinder were tapped. Water dripped from the cylinder and rose to its top. After a 24-hour cure, the unconfined compressive strength of this specimen was 94 psi.

In a fourth experiment, two mixes were prepared. In each, Portland cement (60g) and gypsum (60g) were mixed with sand (600g), then seawater (120g) was added and mixed. This mix was transferred to a cylinder which was tapped vertically on a table to compact it. One mix cured for three hours; its unconfined compressive strength was 31 psi. The second mix cured for 25 hours; its unconfined compressive strength was 61 psi.

In a fifth experiment, two mixes were prepared. In each, Portland cement (75g) and gypsum (75g) were mixed with sand (600g). Then seawater (120g) was added and mixed. These mixes were transferred to cylinders which were tapped vertically on a table to compact the mixes. One mix was cured for 4½ hours; its unconfined compressive strength was 108 psi. The second mix was cured for 23 hours; its unconfined compressive strength was 99 psi.

In a sixth experiment, Portland cement (75g) and gypsum (75g) were mixed with dry sand (600g) and transferred to a cylinder. Seawater (120g) was poured onto the dry mix and, after 150 minutes, about 3/4 of the bottom surface of the 15.6 cm high column appeared to be wet. After a 23-hour cure, the unconfined compressive strength was 120 psi.

In a seventh experiment, two mixes were prepared. In each, Portland cement (27g) and gypsum (63g) were mixed with sand (600g) which contained seawater (105g). Each mix was transferred to a cylinder and each cylinder was tapped on a table to compact the mix. One mix was cured for three hours; its unconfined compressive strength was 250 psi. The second mix was cured for 22 hours; its unconfined compressive strength was 250 psi.

In an eighth experiment, two mixes were prepared. In each, Portland cement (36g) and gypsum (84g) were mixed with sand (600g) which contained seawater (120g). Each mix was transferred to a cylinder and each cylinder was tapped on a table to compact the mix. One mix was cured for four hours; its unconfined compressive strength was 125 psi. The second mix was cured for 24 hours; its unconfined compressive strength was 200 psi.

In a ninth experiment, two mixes were prepared. In each, Portland cement (45g) and gypsum (105g) were mixed with sand (600g) which contained seawater (120g). Each mix was transferred to a cylinder and each cylinder was tapped on a table to compact the mix. One mix was cured for four hours; its unconfined compressive strength was 164 psi. The second mix was cured for 24 hours; its unconfined compressive strength was 409 psi.

#### REGULATED SET CEMENT:

This early strength cement (66g) was mixed with dry sand (660g) and placed in a cylinder. Seawater (157g) was poured onto the top of the dry mix and seven minutes were required for it to percolate to the bottom of the cylinder. Some seawater drained out. After a 22-hour cure, the core crumbled during stripping of the mold.

In a second experiment, this cement (90g) was mixed with dry sand (600g) and placed in a cylinder. Seawater (150g) was poured onto the top of the dry mix and seven minutes were required for it to percolate to the bottom of the cylinder. After a 21½-hour cure, the core crumbled during stripping of the mold.

In a third experiment, this cement (90g) was mixed with dry sand (600g) and seawater (148g) and placed in a cylinder. Excess water drained from the bottom. The mixture set hard after a 2-hour cure. The unconfined compressive strength was 48 psi.

In a fourth experiment, this cement (90g) was mixed with dry sand (600g) and seawater (105g) and placed in a cylinder. Excess water drained from the bottom. The mixture set hard after 1½ hours. After 18½ hours, the unconfined compressive strength was found to be 93 psi.

In a fifth experiment, this cement (90g) was mixed with dry sand (600g) and seawater (24g) and placed in a cylinder. Seawater (80g) and Igepal® CO-630 (4g) were mixed and poured on the top of the sand-cement-water mixture; a "dry top" was obtained in five minutes. After a 17-hour cure, the core crumbled during stripping of the mold.

In a sixth experiment, this cement (90g) was mixed with dry sand (600g) and seawater (120g) and placed in a cylinder. After a 4-hour cure, the unconfined compressive strength was 31 psi.

In a seventh experiment, the same quantities of materials and methods as those in the sixth experiment were used, but the cure time was increased to 96 hours. The unconfined compressive strength increased to 130 psi.

In an eighth experiment, this cement (120g) was mixed with dry sand (600g) and seawater (120g) and placed in a cylinder. After a 4-hour cure, the core crumbled during stripping of the mold.

In a ninth experiment, the same quantities and methods as those in the eighth experiment were used, but the cure time was increased to 96 hours. The unconfined compressive strength was 931 psi.

In a tenth experiment, this cement (150g) was mixed with dry sand (600g) and seawater (130g) and placed in a cylinder. After a 4-hour cure, the unconfined compressive strength was 255 psi.

In an eleventh experiment, the same quantities and methods as those in the tenth experiment were used, but the cure time was increased to 96 hours. The unconfined compressive strength increased to 1950 psi.

In a twelfth experiment, this cement (120g) was mixed with dry sand (600g) and placed in a cylinder. Seawater (120g) was poured on top of the cement-sand mixture and percolated to a depth of 15.2 cm in 27 minutes (sample height was 15.9 cm). After a 4-hour cure, the core ruptured on stripping of the mold.

In a thirteenth experiment, the same quantities and methods as those used in the twelfth experiment were used, but the cure time was increased to 96 hours. The unconfined compressive strength was 255 psi.

In a fourteenth experiment, this cement (90g) was mixed with dry sand (600g) and placed in a cylinder. Seawater (90g) was poured on top of the cement-sand mixture and a "dry top" was obtained in 7 minutes. After a 4-hour cure, the unconfined compressive strength was 13 psi.

REGULATED SET CEMENT - GYPSUM:

Regulated Set Cement (122.5g) was mixed with gypsum (22.5g) and seawater (100g) and poured onto a column of dry sand (600g). The liquid penetrated 12.7 cm and a "dry top" occurred in 21 minutes. After a 24-hour cure, the unconfined compressive strength was 43 psi.

In the second experiment, identical methods and quantities of materials were used, but a "dry top" was obtained in eight minutes. After a 4½-hour cure, the unconfined compressive strength was 32 psi.

RESORCINOL WATERPROOF GLUE:

This two-component (4 parts resin:1 part hardener) adhesive (100g) was mixed with sand (587g) wet with seawater (23.5g) and transferred to a cylindrical mold. After a 24-hour cure, the unconfined compressive strength was 160 psi.

In a second experiment, the adhesive (90g) was mixed with seawater and poured onto a column of sand (587g) wet with seawater (23.5g). Complete percolation did not occur and the sample was not tested.

In a third experiment, the adhesive (100g) was mixed with methyl alcohol (20g), Igepal® CO-630 (0.3g), and water (20g), and poured onto a column of sand (587g) wet with seawater (23.5g). No penetration occurred.

SODIUM SILICATE:

This material (32.5g) was mixed with seawater (20.4g) and then mixed with a solution of sodium bicarbonate (2.7g) in tap water (53g) and poured onto a column of sand (587g) wet with seawater (23.5g). The core ruptured during stripping of the mold.

In a second experiment, the above materials were used in the same quantities except that seawater was used instead of tap water for making the sodium bicarbonate solution. On mixing, the sodium silicate and sodium bicarbonate solutions reacted instantly to form a gel.

SOILTEX®:

This lignin sulfonate material (50g) was mixed with seawater (100g) and poured onto a column of dry sand. It percolated rapidly. After 24 hours, the sample was soft and wet; after eight days, a crust had formed on the surface, but the rest of the core was still wet and soft.

TAKENAKA T-009:

This polyisocyanate material (90g) mixed with accelerator (2.7g) was poured onto a column of sand (600g) wet with seawater (24g). A reaction started near the top of the column and penetration by the additive did not occur.

In a second experiment, T-009 (90g) mixed with accelerator (0.45g) was poured onto a column of sand (600g) wet with seawater (24g). A "dry top" was noted in 40 seconds. After a 24-hour cure, the unconfined compressive strength of the core was 44.5 psi.

In a third experiment, T-009 (90g) mixed with accelerator (0.9g) was poured onto a column of sand (600g) wet with seawater (24g). A "dry top" was noted in 63 seconds and the solution penetrated 12.7 cm in a 15.2 cm column in one hour. After a 24-hour cure, the unconfined compressive strength of the core was 390 psi.

In a fourth experiment, T-009 (90g) mixed with accelerator (0.9g) was poured onto a column of sand (600g) wet with seawater (24g). A "dry top" was noted in one minute and the entire column was penetrated in five minutes. Then seawater (30g) was poured onto the top of the column. After a 65-hour cure, the specimen crumbled on removal from the mold.

TAKENAKA T-018:

Unless otherwise stated, in this series of experiments T-018, a polyisocyanate, (90g) was mixed with C-001 accelerator (varying amounts) and poured onto a column of sand (600g) wet with seawater (24g).

In the first experiment, C-001 (0.9g) was used. A "dry top" was obtained in 42 seconds, and after a 17-hour cure, the unconfined compressive strength was 164 psi.

In a second experiment, C-001 (0.9g) was used. A "dry top" was obtained in 52 seconds, and after a 16-hour cure, the unconfined compressive strength was 340 psi.

In a third experiment, C-001 (0.9g) was used. A "dry top" was obtained in three minutes, and after a two-hour cure, the unconfined compressive strength was 180 psi.

In a fourth experiment, C-001 (1.8g) was used. A "dry top" was obtained in 48 seconds, and after a one-hour cure, the unconfined compressive strength was 510 psi.

In a fifth experiment, C-001 (1.8g) was used. A "dry top" was obtained in 90 seconds, and after a one-hour cure, the unconfined compressive strength was 540 psi.

In a sixth experiment, C-001 (1.8g) was used. A "dry top" was obtained in six minutes, and after a one-hour cure, the unconfined compressive strength was 900 psi.

In a seventh experiment, C-001 (1.8g) was used and the resin, accelerator, sand, and seawater were mixed and then transferred to a cylindrical mold. After a one-hour cure, the unconfined compressive strength was 168 psi.

In an eighth experiment, C-001 (1.8g) was used. A "dry top" was obtained in one minute, and after a one-hour cure, the unconfined compressive strength was 96 psi.

In a ninth experiment, C-001 (1.8g) was used. A "dry top" was obtained in 45 seconds, and after a three-hour cure, the unconfined compressive strength was 153 psi.

In a tenth experiment, C-001 (1.8g) was used. A "dry top" was obtained in 35 seconds, and after a five-hour cure, the unconfined compressive strength was 237 psi.

In an eleventh experiment, C-001 (1.8g) was used. A "dry top" was obtained in one minute and after a four-hour cure, the unconfined compressive strength was 229 psi.

In a twelfth experiment, C-001 (1.8g) was used. A "dry top" was obtained in 78 seconds, and after a 24-hour cure, the unconfined compressive strength was 297 psi.

In a thirteenth experiment, C-001 (1.8g) was used. A "dry top" was obtained in 110 seconds, and after a two-hour cure, the unconfined compressive strength was 177 psi.

In a fourteenth experiment, C-001 (1.8g) was used. A "dry top" was obtained in 65 seconds, and after a  $49\frac{1}{2}$ -hour cure, the unconfined compressive strength was 367 psi.

In a fifteenth experiment, C-001 (2.7g) was used. A "dry top" was obtained in 47 seconds, and after a 24-hour cure the unconfined compressive strength was 550 psi.

In a sixteenth experiment, C-001 (2.7g) was used. A "dry top" was obtained in 45 seconds, and after a one-hour cure, the unconfined compressive strength was 410 psi.

In a seventeenth experiment, C-001 (2.7g) was used. A "dry top" was obtained in six minutes, and after a 2-hour and 35-minute cure, the unconfined compressive strength was 626 psi.

In an eighteenth experiment, C-001 (2.7g) was used. A "dry top" was obtained in 3 minutes, 20 seconds, and after a two-hour cure, the unconfined compressive strength was 560 psi.

In a nineteenth experiment, C-001 (2.7g) was used. A "dry top" was obtained in 93 seconds, and after a one-hour cure, the unconfined compressive strength was 394 psi.

In a twentieth experiment, C-001 (2.7g) was used. A "dry top" was obtained in two minutes, eight seconds, and after a three-hour cure, the unconfined compressive strength was 430 psi.

In a twenty-first experiment, C-001 (2.7g) was used. A "dry top" was obtained in 65 seconds, and after a 5-hour cure, the unconfined compressive strength was 392 psi.

In a twenty-second experiment, C-001 (2.7g) was used. A "dry top" was obtained in 68 seconds, and after a 24-hour cure, the unconfined compressive strength was 415 psi.

In a twenty-third experiment, C-001 (2.7g) was used. A "dry top" was obtained in 97 seconds, and after a 48-hour cure, the unconfined compressive strength was 512 psi.

In a twenty-fourth experiment, C-001 (2.7g) was used. A "dry top" was obtained in 2 minutes, 45 seconds, and after a four-hour cure, the unconfined compressive strength was 550 psi.

In a twenty-fifth experiment, C-001 (2.7g) was used. A "dry top" was obtained in 42 seconds, and after a one-hour cure, the unconfined compressive strength was 277 psi.

In a twenty-sixth experiment, C-001 (2.7g) was used. A "dry top" was obtained in 85 seconds, and after a one-hour cure, the unconfined compressive strength was 361 psi.

In a twenty-seventh experiment, C-001 (2.7g) was used. A "dry top" was obtained in 40 seconds, and after a 17-hour cure, the unconfined compressive strength was 421 psi.

In a twenty-eighth experiment, C-001 (2.7g) was used. A "dry top" was obtained in 80 seconds, and after a four-hour cure, the unconfined compressive strength was 395 psi.

In a twenty-ninth experiment, C-001 (2.7g) was used. A "dry top" was obtained in 97 seconds, and after a 26-hour cure, the unconfined compressive strength was 522 psi.

In a thirtieth experiment, C-001 (2.7g) and toluene (9.0g) were used. A "dry top" was obtained in two minutes, and after a one-hour cure, the unconfined compressive strength was 505 psi.

In a thirty-first experiment, C-001 (4.0g) was used. A "dry top" was obtained in 4½ minutes, and after a five-hour cure, the unconfined compressive strength was 554 psi.

In a thirty-second experiment, C-001 (5.4g) was used. A "dry top" was obtained in two minutes, three seconds, and after a two-hour cure, the unconfined compressive strength was 518 psi.

In a thirty-third experiment, C-001 (5.4g) was used. A "dry top" was obtained in 4½ minutes, and after a four-hour cure, the unconfined compressive strength was 513 psi.

In a thirty-fourth experiment, C-001 (5.4g) was used. A "dry top" was obtained in one minute, and after a 19½-hour cure, the unconfined compressive strength was 678 psi.

#### TAKENAKA T-020:

This polyisocyanate material was used alone, with accelerator C-852, with polyisocyanate T-025, and with various additives.

In a first experiment, T-020 (88g) was mixed with dry sand (587g) and transferred to a mold. After a 48-hour cure, the upper and lower portions of the core were hard, but the center was very weak. The core broke during stripping of the mold.

In a second experiment, T-020 (88g) was mixed with sand (587g) wet with seawater (24g) and transferred to a mold. After a 48-hour cure, the unconfined compressive strength was 490 psi.

In a third experiment, the same quantities and method as those in the second experiment were used. After a 24-hour cure, the unconfined compressive strength was 370 psi.

In a fourth experiment, T-020 (88g) was poured onto a 10.8 cm column of sand (587g). The rate of percolation was very slow and, after 24 hours, the material was still soft. After a 48-hour cure, the unconfined compressive strength was 665 psi.

In a fifth experiment, T-020 (88g) was poured onto a 14 cm column of sand (587g). A "dry top" was obtained in 23 minutes. One minute later, seawater was added to a depth of 0.3 cm. This penetrated 8.9 cm in six minutes and penetrated 11.4 cm in 48 hours. The unconfined compressive strength of the cured sample was 514 psi.

In a sixth experiment, T-020 (88g) was poured onto a column of sand (587g) wet with seawater (24g). A "dry top" was obtained in 35 minutes and a penetration of 11.4 cm occurred in 24 hours. The core had poor abrasion resistance, but its unconfined compressive strength was 462 psi.

In a seventh experiment, T-020 (66.9g) was mixed with C-852 (2.0g), seawater (22g), and sand (580g) wet with seawater (23.2g) and transferred to a mold. There was an almost immediate reaction with expansion. After a 1-hour and 38-minute cure, the core was removed from the mold. It could be broken apart by hand.

In an eighth experiment, T-020 (44.6g) was mixed with C-852 (0.4g) and sand (580g) wet with seawater (23.2g) and transferred to a mold. After a 24-hour cure, the unconfined compressive strength was 70 psi.

In a ninth experiment, T-020 (88g) was mixed with C-852 (0.5g) and sand (587g) wet with seawater (23.5g) and transferred to a mold. In ten minutes, the 14.6 cm column increased 1.9 cm in height. After a 48-hour cure, the unconfined compressive strength was 157 psi.

In a tenth experiment, T-020 (88g) was mixed with C-852 (0.25g) and sand (587g) wet with seawater (24g) and transferred to a mold. In 25 minutes, the 14 cm column increased 0.6 cm in height. After a 48-hour cure, the unconfined compressive strength was 262 psi.

In an eleventh experiment, T-020 (88g) was mixed with C-852 (0.1g) and sand (587g) wet with seawater (24g) and transferred to a mold. After a 48-hour cure, the unconfined compressive strength was 262 psi.

In a twelfth experiment, T-020 (44g) was mixed with T-025 (44g) and poured onto a 14 cm column of sand (587g) wet with seawater (24g). A "dry top" was obtained in nine minutes and an 11.4 cm penetration was obtained in 24 hours. The unconfined compressive strength was 450 psi.

In a thirteenth experiment, T-020 (51g) was mixed with T-025 (51g) and sand (679g) wet with seawater (27g) and transferred to a mold. After a 24-hour cure, the unconfined compressive strength was 342 psi.

In a fourteenth experiment, T-020 (102g) was mixed with T-025 (102g) and poured onto a column of sand (679g) wet with seawater (27.2g). In 40 minutes, a reaction started and the solution reached the bottom in 41 minutes. Excess T-020/T-025 solution (67g) passed out the bottom of the column; thus, the quantities of T-020 and T-025 used were 68.5g of each. After a 24-hour cure, the unconfined compressive strength was 349 psi.

In a fifteenth experiment, T-020 (44g) and T-025 (44g) were mixed with sand (587g) wet with seawater (24g) and transferred to a mold. After a 24-hour cure, the unconfined compressive strength was 445 psi.

In a sixteenth experiment, T-020 (29.5g) and T-025 (29.5g) were mixed with sand (587g) wet with seawater (24g) and transferred to a mold. After a 24-hour cure, the unconfined compressive strength was 200 psi.

In a seventeenth experiment, T-020 (14.5g) were mixed with sand (587g) wet with seawater (24g) and transferred to a mold. After a 24-hour cure, the unconfined compressive strength was 39 psi.

In an eighteenth experiment, T-020 (44g) and T-025 (44g) were mixed with sand (587g) wet with seawater (24g) and transferred to a mold. After a seven-hour cure, the unconfined compressive strength was 310 psi.

In a nineteenth experiment, T-020 (29.5g) and T-025 (29.5g) were mixed with sand (587g) wet with seawater (24g) and transferred to a mold. After a five-hour cure, the core ruptured during stripping of the mold.

In a twentieth experiment, T-020 (88g) was mixed with acetone (21.1g) and poured onto a column of sand (587g) wet with seawater (24g). A "dry top" was obtained in two minutes and, after a 48-hour cure, the unconfined compressive strength was 310 psi.

In a twenty-first experiment, T-020 (88g) was mixed with dibutyl phthalate (20g) and poured onto a column of sand (587g) wet with seawater (24g). A "dry top" was obtained in 11 minutes, and after a 48-hour cure, the unconfined compressive strength was 155 psi.

In a twenty-second experiment, T-020 (88g) was mixed with ethyl silicate-40 (20g) and poured onto a column of sand (587g) wet with seawater (24g). A "dry top" was obtained in 23 minutes, and after a 48-hour cure, the unconfined compressive strength was 372 psi.

In a twenty-third experiment, T-020 (88g) was mixed with ethyl acetate (18g) and poured onto a column of sand (587g) wet with seawater (24g). A "dry top" was obtained in three minutes and, after a 96-hour cure, the unconfined compressive strength was 229 psi.

In a twenty-fourth experiment, T-020 (88g) was mixed with ethylene glycol (20g) and poured onto a column of sand (587g) wet with seawater (24g). A "dry top" was obtained in 33 minutes, and after a 24-hour cure, the unconfined compressive strength was 328 psi.

In a twenty-fifth experiment, T-020 (88g) was mixed with triacetin (18g) and poured onto a column of sand (587g) wet with seawater (24g). A "dry top" was obtained in 14 minutes and, after a 96-hour cure, the unconfined compressive strength was 350 psi.

In a twenty-sixth experiment, T-020 (88g) was mixed with methyl salicylate (20.1g) and poured onto a column of sand (587g) wet with seawater (24g). A "dry top" was obtained in 15 minutes and, after a 96-hour cure, the unconfined compressive strength was 118 psi.

In a twenty-seventh experiment, T-020 (88g) was mixed with hydrolyzed ethyl silicate-40 (20g) and poured onto a column of sand (587g) wet with seawater (24g). Percolation was very slow, but after a 48-hour cure, the unconfined compressive strength was 265 psi.

#### TAKENAKA T-025:

This polyisocyanate material was used alone, with accelerator C-855, and with accelerator C-855 plus various additives.

In a first experiment, T-025 (100.8g) was poured onto a column of sand (565g) wet with seawater (113g). After a 72-hour cure, the unconfined compressive strength was 314 psi.

In a second experiment, T-025 (67.7g) was mixed with sand (565g) and transferred to a mold. After a 72-hour cure, the unconfined compressive strength was 272 psi.

In a third experiment, T-025 (67.2g) was mixed with sand (527g) wet with seawater (21.1g). After a 1½-hour cure, the core ruptured on stripping.

In a fourth experiment, T-025 (88g) was poured onto a column of sand (587g) wet with seawater (23.6g). A "dry top" was obtained in five minutes, and after a 48-hour cure, the unconfined compressive strength was 322 psi.

In a fifth experiment, T-025 (88g) was mixed with sand (587g) and transferred to a mold. After a 48-hour cure, the core ruptured during handling.

In a sixth experiment, seawater (139g) was poured onto a column of sand (587g) to saturate it. Then T-025 (88g) was poured onto the saturated sand and it percolated very slowly and penetrated 10.2 cm. Only the top 1.3 cm of the column hardened.

In a seventh experiment, T-025 (88g) was mixed with C-855 (0.18g) and poured onto a column of sand (587g) wet with seawater (23.6g). A "dry top" was obtained in 12 minutes and, after a 48-hour cure, the unconfined compressive strength was 600 psi.

In a eighth experiment, T-025 (88g) was mixed with C-855 (0.18g) and sand (587g) wet with seawater (23.6g) and transferred to a mold. After a 48-hour cure, the unconfined compressive strength was 540 psi.

In a ninth experiment, T-025 (63.3g) was mixed with C-855 (0.31g) and sand (574g) wet with seawater (23g) and transferred to a mold. After a 72-hour cure, the unconfined compressive strength was 272 psi.

In a tenth experiment, T-025 (65.6g) was mixed with C-855 (0.33g) and sand (574g) wet with seawater (57.4g) and transferred to a mold. After a 72-hour cure, the unconfined compressive strength was 274 psi.

In an eleventh experiment, T-025 (65.6g) was mixed with C-855 (0.33g) and Igepal<sup>®</sup> CO-630 (1g). An emulsion formed. This was poured onto a column of sand (592g) wet with seawater (118g). After a 72-hour cure, the unconfined compressive strength was 210 psi.

In a twelfth experiment, T-025 (67.5g) was mixed with C-855 (0.34g) and sand (511g) and seawater (20.4g) was added. The mix was transferred to a mold, and after a four-hour cure, the unconfined compressive strength was 110 psi.

In a thirteenth experiment, T-025 (66.7g) was mixed with C-855 (0.33g) and sand (517.5g) and seawater (51.7g) was added. The mix was transferred to a mold, and after a four-hour cure, the unconfined compressive strength was 91 psi.

In a fourteenth experiment, T-025 (87.5g) was mixed with C-855 (0.11g) and poured onto a column of sand (579g) wet with seawater (23g). A "dry top" was obtained in four minutes and, after a 24-hour cure, the unconfined compressive strength was 93.5 psi.

In a fifteenth experiment, T-025 (98.5g) was mixed with C-855 (0.12g) and poured on a column of sand (599g) wet with seawater (24g). The mix was added in four passes over a period of 12 minutes to simulate a field operation. After a 24-hour cure, the unconfined compressive strength was 113 psi.

In a sixteenth experiment, T-025 (80g) was emulsified with seawater (20g) by mixing with Cab-O-Sil<sup>®</sup> (1g). This emulsion did not penetrate into the sand.

In a seventeenth experiment, T-025 (82g) was mixed with C-855 (0.2g) and ethyl acetate (18g) and poured onto a column of sand with four percent added moisture (seawater). A "dry top" was obtained in one minute, and after a 20-hour cure, the unconfined compressive strength was 308 psi.

In an eighteenth experiment, T-025 (87.5g) was mixed with C-855 (0.22g) and Cellosolve® (8g) and poured onto a column of sand (552g) wet with seawater (22g). A "dry top" was obtained in eight minutes, and after a 24-hour cure, the unconfined compressive strength was 137 psi.

In a nineteenth experiment, T-025 (87.5g) was mixed with C-855 (0.26g) and dichloromethane (10.7g) and poured onto a column of sand with ten percent added moisture (seawater). After a 17-hour cure, the unconfined compressive strength was 63 psi.

In a twentieth experiment, T-025 (80.1g) was mixed with C-855 (0.2g) and dioctyl phthalate (14.8g) and poured onto a column of sand with four percent added moisture (seawater plus one percent Igepal® CO-630). A "dry top" was obtained in 15 minutes and, after a 20-hour cure, the unconfined compressive strength was 98 psi.

In a twenty-first experiment, T-025 (82g) was mixed with C-855 (0.2g) and triacetin (23.2g) and poured onto a column of sand with four percent added moisture (seawater). A "dry top" was obtained in four minutes and, after a 20-hour cure, the unconfined compressive strength was 450 psi.

#### TAKENAKA T-118:

This polyisocyanate material (90g) was mixed with accelerator (0.01g) and poured onto a column of sand (600g) wet with seawater (24g). A "dry top" was obtained in 40 seconds and, after a 65-hour cure, the core ruptured in stripping of the mold.

#### TERRA KRETE®:

This synthetic resin emulsion (37.5g) was mixed with seawater (112.5g) and poured onto a column of sand (600g). A "dry top" was obtained in 95 seconds, but after four hours, no cure had occurred.

In a second experiment, the same quantities of materials as those in the first experiment were used. A "dry top" was obtained in two minutes, 23 seconds, but after a 24-hour cure, the core crumbled when removed from the mold.

#### X2000:

This vegetable oil base polymer (22.5g) was mixed with seawater (67.5g) and poured onto a column of sand (600g). A "dry top" was obtained in 40 seconds, but after four hours, the core was not sufficiently cured to be removed from the mold and, after 24 hours, it crumbled when removed from the mold.

In a second experiment, the same quantities of materials as those used in the first experiment were used. A "dry top" was obtained in 50 seconds, but after a 96-hour cure, it crumbled when removed from the mold.